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Implications of Microwave Spectroscopy for the Water-Vapor Content of the Venus Atmosphere
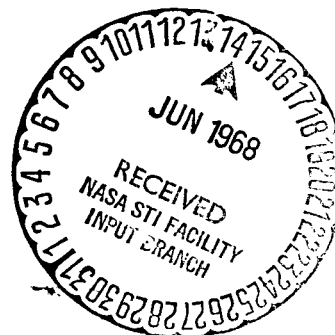
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IMPLICATIONS OF MICROWAVE SPECTROSCOPY FOR THE
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Abstract.   From a comparison of theoretical and observed microwave brightness temperatures of Venus at 1.35 cm, the center of a water-vapor line, we obtain an upper limit of 0.8 percent to the water-vapor mixing ratio in the lower atmosphere.   This limit is consistent with the amount of water vapor detected by Venera 4, the existence of water ice clouds, and a greenhouse effect caused by water vapor and carbon dioxide.   The computed spectra suggest that a sensitive procedure for detecting water vapor is an examination of the 1-cm to 1.4-cm wavelength region.

As a result of the data obtained by the Venera 4 ([1], [2]) and Mariner V spacecraft ([3]), we now know the atmospheric structure of Venus sufficiently well to permit the construction of rather unambiguous microwave spectra. In this paper we compute brightness temperature spectra so as to set limits on the amount of water vapor in the lower atmosphere. These values are compared with the amount of water vapor detected by Venera 4.

In accord with the high temperature conditions found by Venera 4 and Mariner V, we assumed that the radio emission from Venus emanates from a hot surface and atmosphere and that the decline in brightness temperature at wavelengths shortward of 3 cm is attributable to atmospheric opacity. We now describe our method of calculation.

To compute the brightness temperature, we integrated analytically Eq. 3 of a paper by Pollack and Sagan ([4]) over the disk and used a constant solid-angle average emissivity. The brightness temperature is a function of the microwave opacity at each atmospheric level, the atmospheric structure, and the surface emissivity.

We considered three sources of microwave opacity: pressure-induced transitions of carbon dioxide and nitrogen, and permitted, rotational transitions of water vapor. For the absorption coefficient of a carbon dioxide-nitrogen mixture, we used the empirical formula of Ho et al. ([5]). Barrett and Staelin ([6]) presented an equation for the absorption coefficient of water vapor, suggested by Chung ([7]). The absorption coefficient consists of a resonant term, due to the 1.35-cm line, and a nonresonant component, due to the overlapping wings of lines at shorter wavelengths. Chung derived his expression theoretically and adjusted one parameter to give a good fit with a laboratory spectrum near STP. To test the validity of the formula at high pressures and elevated temperatures, we compared it with the laboratory results of Ho et al. ([5]). At the high pressures (45 to 125 atm), temperatures (393°K to 473°K), and wavelength (3.2 cm) used in the latter measurement, the non-resonant component is dominant; Ho et al. have no direct estimate of the resonant term. We find very good agreement between the two formulas

near room temperature, but marked disagreement in the temperature depen-
dence of the absorption coefficient. Accordingly, we have used Chung's
formula in our computations, with the temperature dependence of the line-
width parameter, $\Delta\nu$, modified from $T^{-0.625}$, as given by Chung, to $T^{-2.5}$,
as found by Ho et al. (5).

The atmospheric structure was chosen to fit the measurements of
Venera 4 (1, 2) and Mariner V (3) quite closely. The temperatures and pres-
sures at the position measured by Mariner V probably closely resemble the
average properties of the atmosphere: The atmosphere exhibits no appreciable
diurnal variations (3), as would be expected on the basis of the large heat
capacity of the atmosphere. Furthermore, the measurements were performed
at a midlatitude position of 37°. We will consider two models: For Model I,
the average surface temperature equals the surface temperature at the posi-
tion viewed by Mariner V. Model II differs from Model I only in having an
average surface temperature 25° K lower than does Model I.

We now describe the detailed properties of Model I. There are three
temperature domains: an adiabatic regime beginning at the pressure level of
4.05 atm and extending to the surface (2), a constant lapse rate of 7.9° K/km
between the top of the adiabatic region and the tropopause temperature point
of 230° K, and an isothermal profile above the tropopause (3). We assumed
the carbon dioxide mixing ratio was 85 percent, with the remainder of the
atmosphere consisting of water vapor and nitrogen (1, 2, 3). The temperature
at the 5.08 atm level was chosen as 437° K (3). Richard Wattson (8)
estimated the surface temperature and pressure for us by means of a com-
puter program for adiabatic profiles, which allowed for the variation of the
ratio of specific heats with temperature and pressure. Extrapolating from
the 5.08-atm point to the radar radius of Venus (9), he obtained a surface
temperature of 747° K and a surface pressure of 91.2 atm. We note that our
computer program also allowed for a variable specific heats ratio within the
adiabatic portion of the atmosphere.

We selected a value of 0.82 for the surface emissivity: The fresnel
reflectivity equations were used to average over solid angle a radar cross
section of 0.14 at 70-cm wavelength (10).

A most important feature of our calculations was the allowance for a rapid decrease in the water-vapor mixing ratio above the level at which saturation is first reached. Since the resonant term of the water-vapor absorption coefficient varies inversely with pressure near the 1.35-cm line center, regions of low pressure can significantly influence the microwave spectrum near this wavelength. By allowing for saturation, we obtained only relatively shallow dips in the brightness temperature near 1.35 cm.

Once saturation is attained, condensation will occur and the water-vapor partial pressure will follow a saturation curve to the cloud tops. By analogy with the earth (11), the relative humidity in the stratosphere would probably be quite low. Finally, at sufficiently high altitudes, photodissociation of water vapor will occur. We have attempted to simulate the above situation by having the water-vapor mixing ratio decrease exponentially above the saturation point with a 1-km scale height, a value appropriate for the water-vapor saturation curve. Changes in the value of the scale height by a factor of 4 did not significantly alter the computed spectra.

We performed spectral calculations of brightness temperature with a computer program written initially by Andrea Dupree, and modified substantially by one of the authors (A. T. W.). Integration step sizes of 1 km were used in performing the vertical integration.

Figures 1 and 2 present the results of the calculated brightness temperature spectra for six values of the water-vapor mixing ratio: 0 percent, 0.1 percent, 0.3 percent, 0.5 percent, 1 percent, and 3 percent. Also given are measurements of brightness temperature near inferior conjunction with the estimated errors, which were taken from a compilation by Dickel (12). The computed curves are rather insensitive to the exact choice of input parameters, especially in the 0.8-cm to 1.4-cm wavelength range. For the cases of larger water-vapor mixing ratios, less than a 15°K change in brightness temperature resulted in this range when the following changes were simultaneously made: the surface temperature decreased to 543°K (the value estimated by the Venera 4 experimenters); the surface pressure lowered to 20 atm; the

emissivity increased to 0.9; the carbon dioxide mixing ratio changed by ± 15 percent, a constant lapse rate used between tropopause and surface; and the tropopause temperature changed by 15°K. Somewhat larger changes resulted for the cases of lower water-vapor mixing ratio, especially when the carbon dioxide mixing ratio or atmospheric structure was altered.

An interesting feature of Figs. 1 and 2 is the slight displacement short-ward of 1.35 cm of the center of the absorption feature for cases of low water-vapor mixing ratio. For example, the absorption minimum is located at 1.3 cm for the 0.3 percent case. This results from the influence of the· steady increase in brightness temperature toward longer wavelength super-imposed on the decrease caused by the resonance line.

We now set limits on the water-vapor mixing ratio in the lower atmos-phere of Venus. Because of the shallowness of the absorption feature near 1.35 cm in the computed spectra, the depth of the feature is not a very useful discriminant with the present set of data. A more useful criterion is the absolute value of the brightness temperature at 1.35 cm: The curves of Figs. 1 and 2 are markedly different at this wavelength, and as mentioned above the values of the brightness temperature here are relatively independent of the exact values of the input parameters. The following brightness tempera-tures have been measured near inferior conjunction at or quite close to 1.35 cm: 520 ± 40°K (13), 435 ± 40°K (14), 404 ± 28°K (15), 500 ± 70°K and 560 ± 48°K (16), and 436 ± 39°K (17). Accordingly, the brightness tempera-ture at 1.35 cm is probably in excess of 375°K and water-vapor mixing ratios in the lower atmosphere greater than 0.8 percent can be excluded. Unfor-tunately, the present observations do not permit the setting of a lower bound other than 0 percent.

The above upper limit is compatible with a value of between 0.1 percent and 0.7 percent determined by the chemical analysis experiment aboard Venera 4 (1, 2). It also does not exclude the presence of water condensation clouds in the upper atmosphere of Venus. Such clouds would have cloud-bottom temperatures below the equilibrium freezing point of water and so, except for possibly some supercooled droplets, they would consist of ice

particles. Finally, the above limit does not exclude mixing ratios of water vapor, about 0.5 percent, required for a carbon dioxide, water-vapor green-house effect (18).

Above, we have considered models having water-vapor mixing ratios of 0.1 percent or more for which condensation can be expected to occur in the upper atmosphere. However, the occurrence of condensation for ratios between 0.001 percent and 0.1 percent is uncertain and depends on the exact choice of tropopause temperature. Were the tropopause temperature to be too high so as to preclude condensation for some of these ratios, these cases could be immediately ruled out as being inconsistent with the small, spectro-scopically determined amounts of water vapor in the upper portion of the atmosphere (19). Finally, no condensation will occur with values less than 0.001 percent, and conceivably spectra produced for such models would con-tain very deep, narrow absorption features near 1.35 cm. However, their widths would be much smaller than typical instrumental bandwidths (17), and so a much shallower line would result. In addition, photodissociation may prevent the formation of such an intrinsically deep line by causing a depletion of water vapor in the region of line formation.

The calculated spectra show very broad, shallow depressions near 1.35 cm. Previous searches for the presence of water vapor have been conducted at wavelengths centered around and quite close to 1.35 cm. Perhaps a more profitable procedure would be to investigate the region between 1 and 1.4 cm. For example, the brightness temperature declines by 50°K for the 0 percent case between 1.4 and 1 cm, but increases by 5°K for the 0.5 percent case. Table 1 presents values of the ratio of the brightness temperature at 1.4 cm to that at 1 cm, as well as the absolute value of the brightness temperature at 1 cm.

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Table 1. Computed brightness temperatures at a wavelength of 1 cm, $T_B(1.0)$ and the ratio of brightness temperatures at 1.4 and 1.0 cm, $T_B(1.4)/T_B(1.0)$.

a_{H_2O} * (percent)	$T_B(1.0)$ (°K) Model[†]		$T_B(1.4)/T_B(1.0)$ Model	
	I	II	I	II
0	483	459	1.102	1.107
0.1	464	442	1.061	1.064
0.3	438	419	1.009	1.027
0.5	421	403	0.976	0.996
1.0	395	378	0.939	0.962
3.0	352	338	0.916	0.941

*Water-vapor mixing ratio in the lower atmosphere.

[†]Model I uses the value at the locale explored by Mariner V as the average surface temperature, while Model II uses an average surface temperature that is 25°K lower.
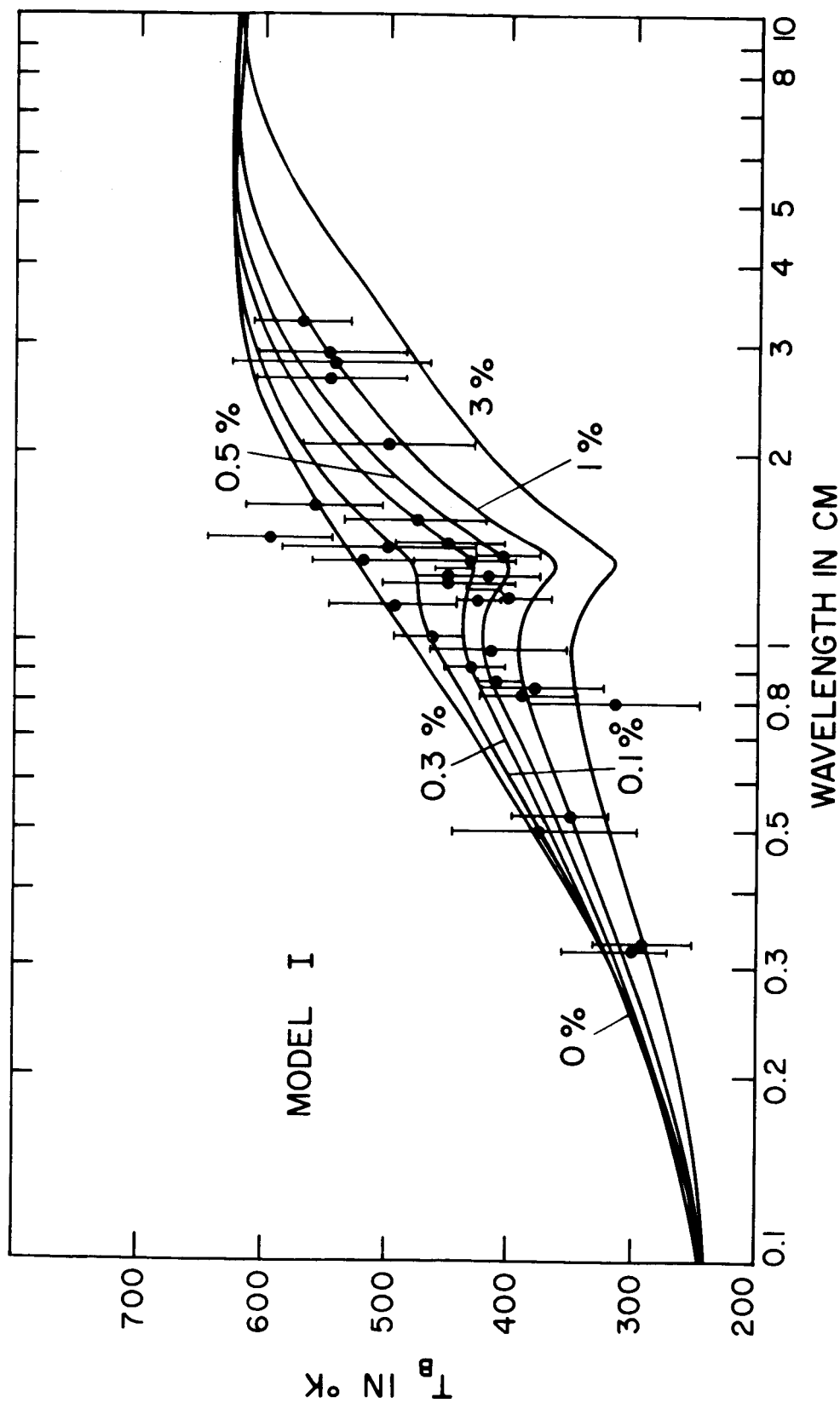
Fig. 1. Brightness temperature, T_B, as a function of wavelength for six values of the water-vapor mixing ratio in the lower atmosphere. The mixing ratio appropriate to each curve is indicated. Observed brightness temperatures, indicated by closed circles with appropriate error bars, are also presented. The average surface temperature equals the surface temperature at the position viewed by Mariner V.
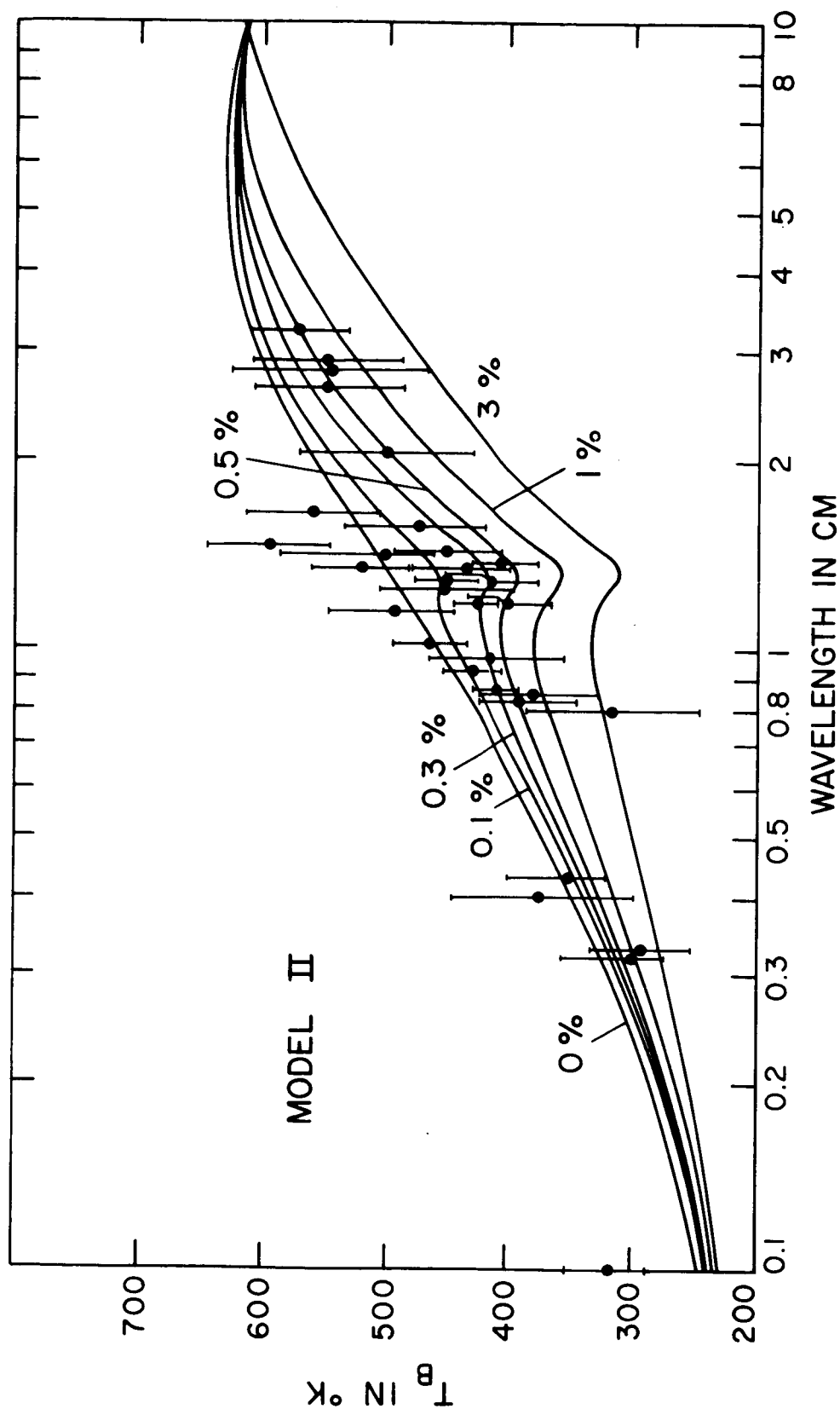
Fig. 2. Brightness temperature, T_B, as a function of wavelength for six values of the water-vapor mixing ratio in the lower atmosphere. The mixing ratio appropriate to each curve is indicated. Observed brightness temperatures, indicated by closed circles with appropriate error bars, are also presented. The average surface temperature is 25°K colder than the surface temperature at the position viewed by Mariner V.